Associated Pair Production of the $\mathcal{SM}$ Higgs and the Probing of the Higgs Self-Coupling

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1 Associated Higgs Pair Production

The interest in double Higgs production is the probing of the triple Higgs self coupling. It has been considered in e^+e^- sometime ago[1]. The most efficient means for double Higgs production is $e^+e^- \to \nu_e\bar{\nu}_e HH$ (see fig. 1). Double Higgs bremstrahlung ($e^+e^- \to ZHH$) is only competing at relatively low energies where the event sample is too low to be useful. The equivalent loop-induced double Higgs production in e^+e^- has been found to be much too small[4] and is not sensitive to the H^3 coupling. However, the $\gamma\gamma$ mode can form a $J_Z = 0$ state and therefore $\gamma\gamma \to HH$ is a candidate for testing the H^3 coupling[3]. It has been pointed out recently that another interesting process is $\gamma\gamma \to W^+W^-HH$ [2] that is expected to compete with double Higgs production in e^+e^- . The reason is that in the TeV range, W fusion processes are very much enhanced. The sub-process involved is $W^+W^- \to HH$, where the dominant helicity amplitude is:

$$\begin{aligned}\tilde{\mathcal{M}}_{LL} &= \frac{g^2}{2}\left\{\frac{1}{\beta_H\beta_W^3}\left(\frac{1}{x-x_0}-\frac{1}{x+x_0}\right)\left(r\frac{M_H^2}{s}+\beta_H^2+\beta_W^4\right)\right. \\ &+ \left.\frac{1}{\beta_W^2}(2-\beta_W^2-r)+\frac{3h_3r}{4}\left(\frac{1+\beta_W^2}{1-M_H^2/s}\right)\right\} \to \frac{g^2}{4}r(3h_3-2)+\ldots \qquad (1)\end{aligned}$$

Where h_3 is the anomaly in the triple Higgs coupling g, *i.e.* $g = h_3 g_{sm}$ where g_{sm} is the minimal standard model coupling of H^3. We also denote $\beta_{W,H} = \sqrt{1-4M_{W,H}^2/s}$, $r = M_H^2/M_W^2$, $x_0 = (1+\beta_H^2)/2\beta_W\beta_H$, $x = \cos\theta$.

Figure 2 shows that at 2TeV, the cross sections drops precipitously with increasing Higgs mass. One can also notice that in $\gamma\gamma \to W^+W^-HH$ the external outgoing W (mainly transverse) are produced at small angle and take a large amount of energy. For the fusion diagrams of this process, the internal W triggers $W^+W^- \to HH$, which implies that these diagrams dominate for a heavy Higgs. When convoluting with the much advertised photon spectra of[5] and for $M_H = 100GeV$ the cross section of $\gamma\gamma \to W^+W^-HH$ drops by about at least a factor of 2 compared with the result without convolution. For W-fusion-like processes, the internal W's are almost on shell and one may wonder if some structure functions could reproduce the exact results.

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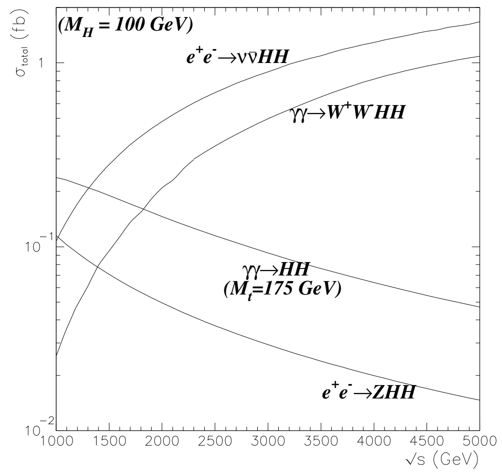

Figure 1: Comparison of cross sections for double Higgs production at e^+e^- and $\gamma\gamma$ reactions for a light Higgs $M_H = 100GeV$.

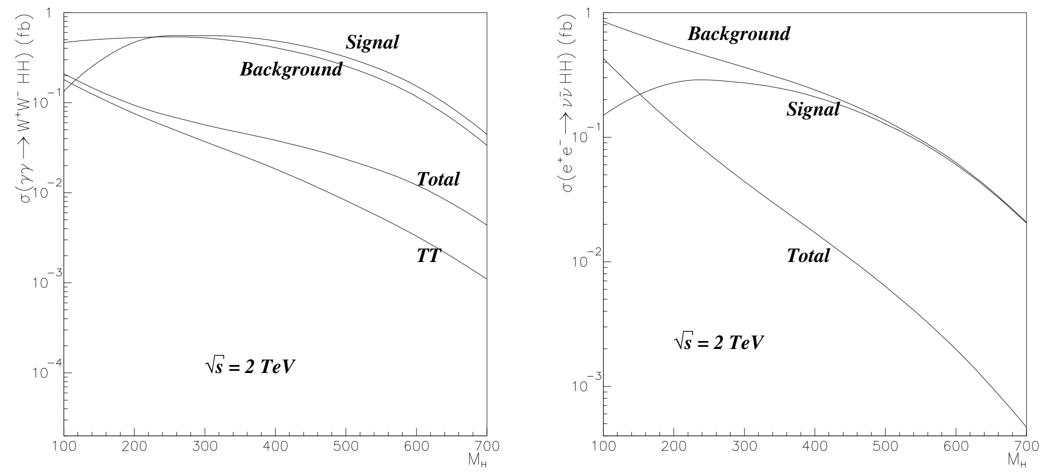

Figure 2: Higgs mass dependence of the $\gamma\gamma \to W^+W^-HH$ cross section at 2TeV. The contribution of the diagrams involving the triple Higgs vertex (Signal) and the rest (Background) is shown separetely. Note the strong interference that occurs in the $\mathcal{SM}$ especially for large M_H.

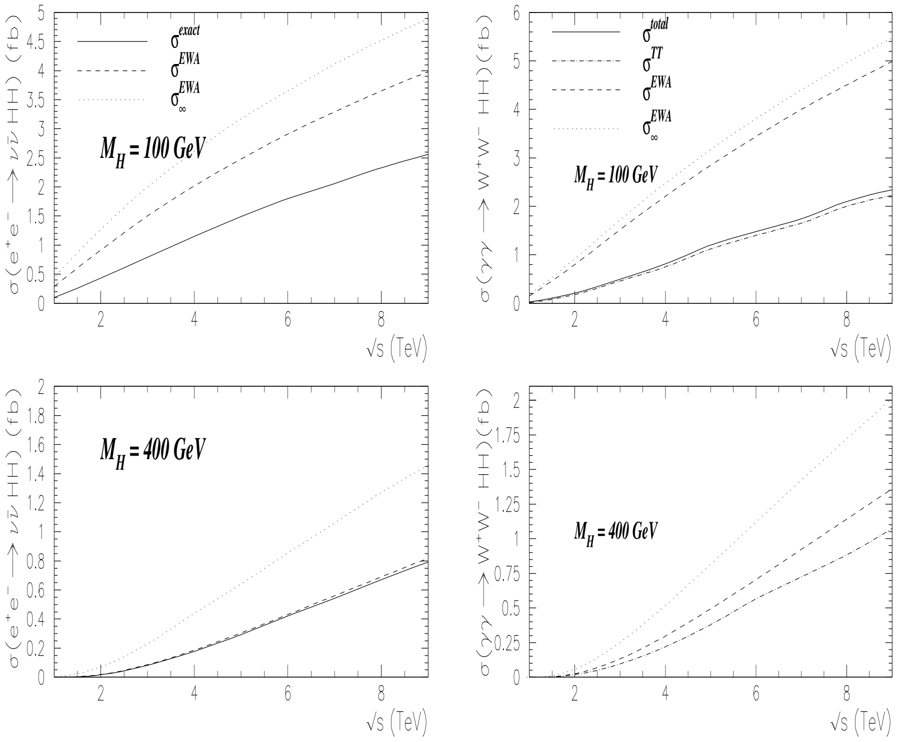

Figure 3: Comparing the result of the W_L effective approximation (σ^{EWA}) to the exact result σ^{exact} for $e^+e^- \to \nu_e \bar{\nu}_e HH$ (left) and $\gamma\gamma \to W^+W^-HH$ (right) for a light Higgs and a heavy Higgs. Also shown is the asymptotic analytical cross section σ^{EWA}_{∞}. σ^{TT} is the cross section with both outgoing W's transverse.

2 The structure function approach

There have been numerous derivations of the distribution (or structure function) of the W inside the light fermions (quarks and electrons) [6]. For the effective W approximation, the most interesting aspect concerns the W_L content, which has been used to investigate manifestations of models of symmetry breaking and Higgs production. The W_L distribution inside the photon has only very recently been studied [7]. For the case of the heavy Higgs the approximation is excellent, already at 2TeV. However, for a light Higgs, the approximation is not good and reproduce only the energy behaviour. If one makes the further approximation that the hard process cross section is independent of the energy, this additional "asymptotic" approximation only reproduces the energy behaviour as well as the order of magnitude (even for a heavy Higgs, see figs. 3).

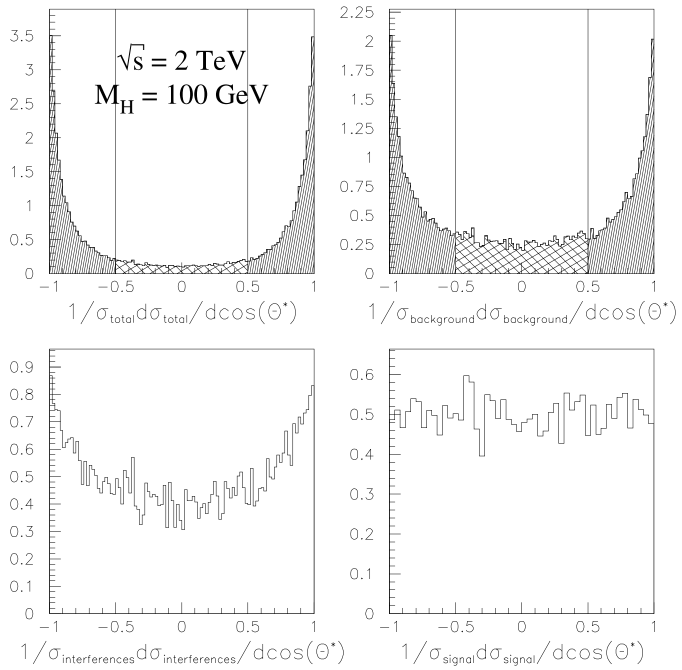

Figure 4: The distribution in the reconstructed angle $\theta^\star$ for the signal, background and the interference in the case of $\gamma\gamma \to W^+W^-HH$ without convolution with photon spectra.

3 Identifying and measuring the Higgs triple vertex

There is a specific signature of the H^3 coupling in all processes that we have studied. Once we note that the two Higgses that originate from this vertex can be regarded as produced by a scalar $H^\star$ then in the centre of mass system of the pair, the angular distribution of the Higgses is flat. Therefore, we suggest to reconstruct the angle, $\theta^\star$, measured in the centre-of-mass of the pair, between the Higgs direction and the boost axis or the direction of the beam. For the "signal"[†] the distribution is flat, while the "background" is peaked in the forward/backward direction (see fig. 4). We therefore consider the ratio R of events that verify $|\cos(\theta^\star)| < \cos(\theta_0^\star)$[‡], over the number of events outside this region. Assuming a total integrated luminosity of $300 fb^{-1}$, and a 50% efficiency for the reconstruction of the double Higgs events one obtain $\sim$ 68 $e^+e^- \to \nu_e\bar{\nu}_e HH$ events for $M_H = 100 GeV$. Here the criterion for detection of an anomaly in h_3 is a 50% deviation in the expected number of events, provided one has at least 30 events. We conclude that with the total cross section one would only be able to claim New Physics if $\delta h_3 < -0.75$ or $\delta h_3 > 2$.

[†] We call "signal" the part of the amplitude that include the H^3 vertex. The rest is called "background".
[‡] $\cos\theta_0^\star = 0.5$ is taken in the following.

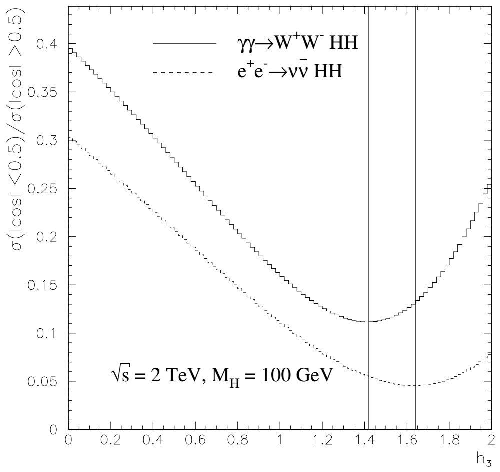

Figure 5: Dependence of the ratio R on h_3.

For $M_H = 400GeV$, $\mathcal{SM}$ values will not lead to a measurement, however if $|\delta h_3| > 1$ a signal will be recorded (with more than 30 events) and would be a clear indication for an anomalous h_3 coupling. For $M_H = 100GeV$ where one has enough events for a $\mathcal{SM}$ value, the ratio R is much more powerful in constraining the coupling. First the event sample within $|\cos\theta^{\star}| < 0.5$ is about 7 out of 60 outside this region. Assuming that the ratio can be measured at 20%, we find $-.10 < |\delta h_3| < .15$ (see fig. 5) which means a precision of about 10% on h_3. For $\gamma\gamma \to W^+W^-HH$ and considering the effective $\gamma\gamma$ luminosity, for $M_H = 100GeV$, one can hope to collect 15 events. In view of this number the criterion for detection of non-standard values is 100% deviation in the number of events. However, for a Higgs mass of 400GeV the effect of an anomalous H^3 coupling are dramatic and, by far, much more interesting than in e^+e^- . Requiring observation of at least 15 events for M_H = 400GeV (within the $\mathcal{SM}$ one expects only 3) useful constraints on the coupling can be set: $-.7 < \delta h_3 < 0.5$. There is thus a complementarity between the e^+e^- and the $\gamma\gamma$ depending on the Higgs mass in probing the Higgs triple vertex. As for the ratio R, taking $M_H = 100GeV$ it is unlikely that with the number of total $WWHH$ events at $\gamma\gamma$ one would be able to make such a measurement, nonetheless even if this ratio were measured with the same precision as in e^+e^- one would not constrain the couplings further than what is achieved in the classic e^+e^- mode. For $M_H > 600GeV$, $\gamma\gamma \to HH$ is the only reaction where useful limits can be set. Thus, there is at a 2TeV collider a very nice coverage of the h_3 sensitivity by all three reactions.

4 Conclusions

We have seen that a 2TeV e^+e^- collider with the realistic luminosities expected for this machine one may hope to achieve a measurement of the tri-linear couplings at the level of 10% (for a light Higgs). The results are also encouraging in the sense that the e^+e^- and the $\gamma\gamma$ modes can cover different ranges of the Higgs mass. We find that for a light Higgs (up to 250GeV) the best limits on the H^3 couplings come from $e^+e^- \to \nu_e \bar{\nu}_e HH$. However, for heavier Higgses up to mass of $500GeV$, the best channel is the associated double Higgs production in $\gamma\gamma$. For still heavier masses, the one-loop induced $\gamma\gamma \to HH$ is by far better. The variable R clearly helps in discriminating the triple Higgs vertex. As a by-product we have verified the validity of the distribution function describing the longitudinal W content of the photon. We should also insist on the complementarity of the e^+e^- and the $\gamma\gamma$ modes of the linear collider for these studies.

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